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Key Points:
- Catchment Morphing (CM) is a novel and potentially powerful approach for ungauged catchments
- CM requires less observed data and is straightforward in modeling ungauged catchments
- The knowledge of percentage runoff can significantly improve the CM runoff predictions

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Catchment Morphing (CM): A Novel Approach for Runoff Modeling in Ungauged Catchments

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Abstract Runoff prediction in ungauged catchments has been one of the major challenges in the past decades. However, due to the tremendous heterogeneity of the catchments, obstacles exist in deducing model parameters for ungauged catchments from gauged ones. We propose a novel approach to predict ungauged runoff with Catchment Morphing (CM) using a fully distributed model. CM is defined as by changing the catchment characteristics (area and slope here) from the baseline model built with a gauged catchment to model the ungauged ones. As a proof of concept, a case study on seven catchments in the UK has been used to demonstrate the proposed scheme. Comparing the predicted with measured runoff, the Nash-Sutcliffe efficiency (NSE) varies from 0.03 to 0.69 in six catchments. Moreover, NSEs are significantly improved (up to 0.81) when considering the discrepancy of percentage runoff between the target and baseline catchments. A distinct advantage has been experienced by comparing the CM with a traditional method for ungauged catchments. The advantages are: (a) less demand of the similarity between the baseline catchment and the ungauged catchment, (b) less demand of available data, and (c) potentially widely applicable in varied catchments. This study demonstrates the feasibility of the proposed scheme as a potentially powerful alternative to the conventional methods in runoff predictions of ungauged catchments. Clearly, more work beyond this pilot study is needed to explore and develop this new approach further to maturity by the hydrological community.

Plain Language Summary For flow forecasting in areas without observed data as reference, we propose a novel approach to transfer from a known area to an unknown area, with the idea of morphing. The approach is a potentially powerful alternative to the conventional methods in runoff predictions of ungauged area.

1. Introduction

Hydrology is a science intimately related to local meteorology, geomorphology, ecology, etc. and highly depends on observation data (Sivapalan, 2003; Zhou et al., 2015). Constrained by the limited knowledge of catchment processes and simplification of hydrological models, it is common to calibrate a hydrological model with observed rainfall and river flow data (Hrachowitz et al., 2013b; Legates & McCabe, 1999; Nash & Sutcliffe, 1970; Sorooshian et al., 1983). Moreover, our current understanding of hydrological responses is far from sufficient to extrapolate from a gauged catchment to an ungauged catchment. Runoff prediction in ungauged catchments has attracted attentions of researchers in the past decades (especially during the 10 year programme on Predictions in Ungauged Basins (PUB), an IAHS initiative operating throughout the decade of 2003–2012) (Hrachowitz et al., 2013a).

It is acknowledged catchment geomorphology acts as a dominant control on runoff production and routing (Beven et al., 1988). Hillslope, catchment size and channel networks, etc. were explored to affect flow volume and travel time (Beven, 2000; Botter & Rinaldo, 2003; Botter et al., 2010; D'Odorico & Rigon, 2003; Robinson et al., 1995), therefore, approaches to derive runoff prediction by considering geomorphological characteristics have been proposed, among which geomorphology-derived instantaneous unit hydrograph (GIUH) (Chutha & Dooge, 1990; Kumar et al., 2007; Rodríguez-Iturbe & Valdes, 1979; Valdés et al., 1979), the width-function instantaneous unit hydrograph (WFIUH) (Grimaldi et al., 2012; Naden, 1992; Rinaldo et al., 1995) and regionalization (Claudia et al., 2016; Oudin et al., 2008) are main approaches widely applied in ungauged catchments. However, GIUH is difficult to present a consistent performance due to its improper assumptions and simplification (Rigon et al., 2016; Robinson et al., 1995; Singh et al., 2014). Moreover, only the topographic characteristics are considered in both GIUH and WFIUH, limitations exist as other catchment properties, e.g., land use, soil types, etc. (Bárdossy, 2006; Botter et al., 2010; Rice et al., 2016), are crucial to runoff predictions as well. Regionalization of catchments is trying to categorize catchments into groups with similar hydrological responses with related indicators, including hydrological, meteorological and catchment characteristics (Castiglioni et al., 2010). As a result, parameters in hydrological models are to be transferred directly within the same group. The difficulty of defining groups, the requirement of numerous gauged catchments and uncertainty in hydrological elements hinder the efficiency to apply regionalization in ungauged catchments (Westerberg et al., 2016). Due to the drawbacks of existing approaches, alternative model approaches should be explored.

It is assumed that a well-tested hydrological model can be treated as a proper representation of the real-world catchment response. Experiments have been done to obtain more knowledge of hydrological processes in a given catchment with the help of a well-tested model (Grimaldi et al., 2010; Nippgen et al., 2011; Zhang et al., 2017), as well as serve as a virtual catchment to return response patterns and dynamic systems responding to changing metrological inputs and boundary conditions (Dunn et al., 2007; Hrachowitz et al., 2013b).

This study presents a novel approach, Catchment Morphing (CM), with a fully distributed model to be used in the ungauged catchment. Creating a model for an ungauged catchment by changing the catchment geomorphology from a baseline model, it is assumed that the created model is representative for the objective catchment as catchment geomorphology is crucial to runoff production. The scheme is clarified with seven catchments in the UK in the study.

2. Methodology and Data Set

2.1. Hydrological Model

Système Hydrologique Européen TRANsport (SHETRAN) is a physically based spatially distributed hydrological model for water flow and sediment and solute transports in catchments (Ewen et al., 2000), which is originated from the Système Hydrologique Européen (SHE) (Abbott et al., 1986). SHETRAN provides an integrated representation of water movements through a catchment, containing major elements of the hydrological cycle as shown in Table 1. It models streamflow in a single complete river catchment by retrieving data for a catchment, including weather data, river gauge recordings, catchment properties, e.g., DEM, land use and soil type. The catchment is represented by an orthogonal grid, which allows spatial distribution of input data, including rainfall, metrological data and catchment properties, etc. The model has been applied in varied catchments and has proved to be a reliable hydrological model (Birkinshaw & Ewen, 2000; Hipt et al., 2017; Norouzi Banis et al., 2004).

2.2. Study Sites and Data Set

Figure 1 shows the locations and river networks of the tested catchments in this study. The baseline catchment was the Brue catchment with a drainage area of 132 km^2, and the average slope is 29.2 m/km. The

Table 1
Equations of Hydrological Processes in SHETRAN

Processes	Equation
Subsurface flow	Variably saturated flow equation (3D) (*Parkin*, 1996)
Overland flow	Saint-Venant equations, diffusion approximation (2D) (*Abbott et al.*, 1986)
Channel flow	Saint-Venant equations, diffusion approximation (flow in a network of 1-D channels)
Canopy interception and drip	Rutter equation (*Abbott et al.*, 1986)
Evaporation	Penman-Monteith equation (or as fraction of potential evaporation rate) (*Abbott et al.*, 1986)
Snowpack and melt[a]	Accumulation equation and energy budget melt equation (or degree-day melt equation) (*Abbott et al.*, 1986)

[a]Snowpack and melt are not considered in this study.

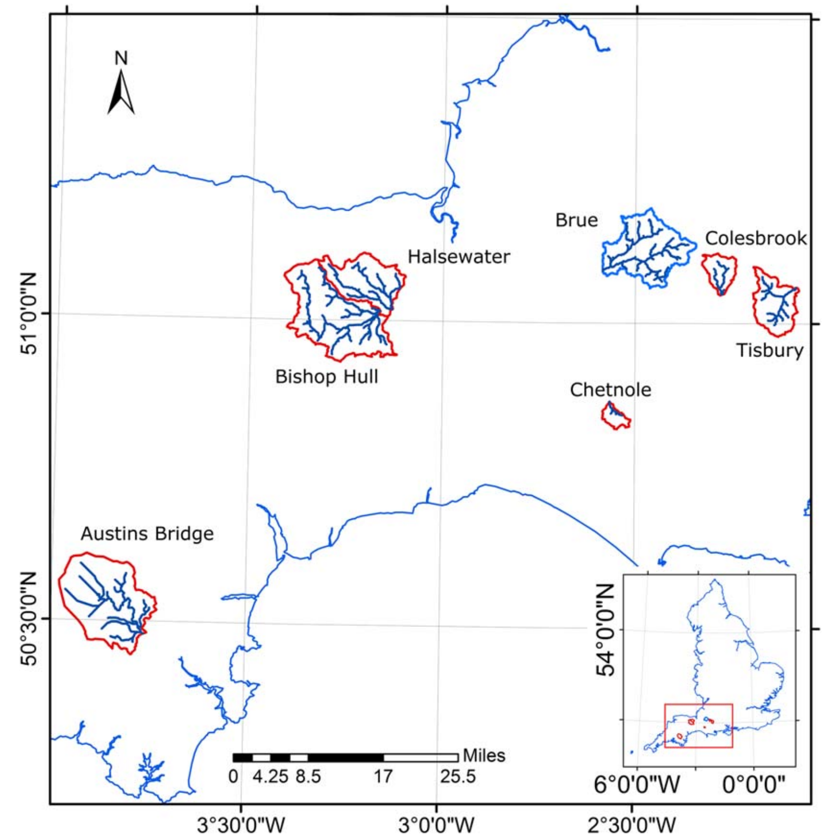

Figure 1. The locations of the tested catchments in the UK.

model was built using SHETRAN with 15 min rainfall and runoff data in the catchment. The catchment was represented by an orthogonal grid with the cell size of 500 m. The soil parameters were determined by the national soil map (Soil Parent Material Model, 2011) and experimental hydrological parameters (Kelly & Cuenca, 1998), however, the soil depth required in the model was unavailable. Therefore, the soil depth was calibrated using data in 1995 and assessed by Nash-Sutcliffe efficiency (NSE) of 0.82 and validated using data in 1996 with NSE of 0.81, indicating the model was good enough to represent the real catchment.

The six catchments for testing are located in the southwest of England, with the basic information including catchment area, average slope, percentage runoff (PR) from Flood Estimation Handbook (FEH) and average annual rainfall shown in Table 2. It is noticed that although the six catchments are in spatial proximity, the climatic, geomorphological and hydrological properties vary significantly.

Table 2
Basic Information of the Catchments

		Name	Area (km^2)	Slope (m/km)	FEH PR (%)	Average annual rainfall (mm)
Baseline catchment		Brue	132	29.2	36.4	867
Testing catchments	1	Tisbury	66	79.5	19.6	891
	2	Austins Bridge	249	121.5	32.8	1770
	3	Chetnole	13	97.5	45.3	989
	4	Colesbrook	57	61.6	40.0	884
	5	Bishop Hull	204	98.0	32.9	964
	6	Halsewater	94	77.6	30.6	851

2.3. Catchment Morphing (CM)

Different from a lumped or semi-distributed model, a fully-distributed model describes a catchment with physically-based processes, as close as possible to the real-world response. Given SHETRAN is built as a baseline model with a gauged catchment that is validated with measured data, a morphed new model can be created by changing the catchment geomorphological characteristics of the baseline model. Since the morphed model is embedded with new characteristics from the ungauged catchment, it is presumed as a representation of the new catchment. This process is defined as Catchment Morphing (CM) in this study.

The six models were created respectively by CM from the baseline model. The catchment area was changed by multiplying the cell size with a ratio of two catchment areas (area of the target catchment/area of the Brue catchment) and the catchment average slope was changed in a similar way. Moreover, the soil parameters were derived from the same source as the Brue catchment. As a result, the created catchments were treated as proper descriptions of the target catchments.

An example is displayed in Figure 2, the target catchment in Figure 2b is the Tisbury catchment with an area of 66 km^2 and average catchment slope of 79.5 m/km. A morphed model for the target catchment was created by changing the slope and catchment area of the baseline model (Figure 2a) to the properties of the target catchment. To maintain a simple morphing process, the baseline model was changed by multiplying the corresponding ratio of catchment size (0.50) and slope (2.72) between the Brue and target catchment. The created model is shown in Figure 2c, in this model, the catchment area is 66 km^2 and the average slope is 79.5 m/km, which is the same with the Tisbury catchment (i.e., the target catchment in Figure 2b). The other catchment characteristics, e.g., the catchment shape and river network, are remained the same with the baseline model (Figure 2a).

2.4. Approach Verification

The six testing catchments were treated as ungauged catchments (i.e., their flow observations were not used on CM) and assigned with a morphed model respectively with the slope and area. The runoffs in the six catchments were predicted using the morphed models with the local rainfall data. The 15 min data from 1 October 1998 to 1 January 1999 were chosen in this study for all the catchments. The assessment of the approach includes:

1. Original model performance: The original model runoff was generated directly from the morphed model.
2. Model performance adjusted with PR: When calculating the PR of the predictions in all the catchments, it was found that PR varied from 19.2% to 51.8% in the study period. As PR is an intuitive index to describe runoff magnitude in a catchment (Savenije, 1996; Sawicz et al., 2014), it was rational to consider adjusting the predicting runoff with PR in this study.

   Two types of PR were adopted to illustrate the potential to improve the model performance. One is FEH PR derived from soil types and another is the real PR derived from the observed runoff.

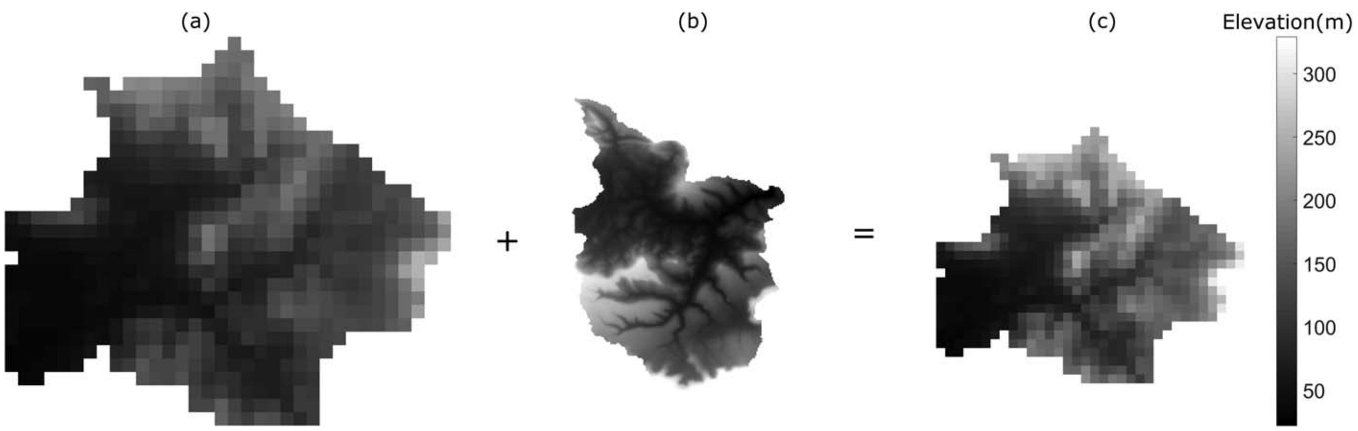

Figure 2. An example of Catchment Morphing, (a) the baseline model built with the Brue catchment, (b) the target catchment: Tisbury catchment, (c) the morphed model from the baseline model but with catchment characteristics (slope and area) of the Tisbury catchment.

3. Model performance compared with a traditional method: An empirical UH proposed by FEH (FEH is the standard method used by water practitioners in the UK and some other countries), described with four catchment descriptors (e.g., catchment slope, drainage length, urban extent and soil moisture) analyzed from 1,822 events in 204 catchments, has been widely used in the UK for gauged and ungauged catchments. The comparison of the model performance with CM and the FEH UH was further demonstrated for the approach verification.

3. Results

3.1. Original Model Performance

The performance of the model is presented with NSE labeled as Original in Table 3 and hydrographs shown in Figure 3. The total length of the time series is 8832 time steps with the observed streamflow shown in the small rectangle in each subfigure in Figure 3. To clearly demonstrate the goodness of runoff predictions, part of the hydrographs, including the highest peak volume and several small peaks, are extracted in the subfigures. The positions of the chosen periods are displayed with the dashed line in the rectangles.

According to the results, NSE varied from 0.03 to 0.69 in the original prediction. The predicted runoff in Tisbury (Figure 3a) was reasonably well in reproducing in the second largest peak (observed 21.99 m^3/s, modeled 19.32 m^3/s at time 505). However, the largest peak volume at time 1212 was significantly underestimated (observed 22.19 m^3/s, modeled 11.55 m^3/s). Austins Bridge experienced several underestimations in peak flows (observed 98.00 m^3/s, modeled 45.45 m^3/s at the largest peak) and fluctuations in the recession part. The predictions of Chetnole and Colesbrook (Figures 3c and 3d) were evidently lower than the observed data with both relative errors higher than 67.5% at the largest peaks. Overestimations in both Bishop Hull and Halsewater (Figures 3e and 3f) were observed especially at the recession. Based on the model performance, the original predictions were not good enough to be spread to broad applications. Nevertheless, it was worthwhile noticing that although discrepancies existed in runoff prediction magnitude, the modeled hydrograph shapes were highly consistent with the measured data. Therefore, a reasonable adjustment of the prediction magnitude would likely bring certain improvement to the results.

3.2. Model Performance Adjusted With FEH PR

As stated in section 2.4, PR is capable of describing the magnitude of the runoff and was adopted to improve the model performance. Standard PR derived from the Hydrology Of Soil Types (HOST) (Boorman et al., 1995) in 943 catchments in the UK was published in the FEH (Robson & Reed, 1999), which is recognized as FEH PR in this study. The FEH PR the baseline and target catchments are listed in Table 2. As the Tisbury catchment is not included in the FEH, the FEH PR from the nearest catchment was used.

It was inferred from Figure 3 that when FEH PR of the target catchment was lower than that of the Brue catchment, the prediction runoff was prone to be overestimated, and vice versa. For example, the FEH PR in Chetnole is 45.3%, which is higher than that of 36.4% in Brue. Accordingly, the streamflow was underestimated by the morphed model, which showed a consistent trend between PR discrepancy and runoff predicting error. Therefore, an adjustment ratio (target PR/Brue PR) was applied for runoff predictions in all catchments, with NSE values shown in Table 3 and hydrographs in Figure 3. Apart from Tisbury and Austins Bridge, it showed improvements using the adjusted runoff with the best improvement of NSE from 0.39 to 0.71 in Halsewater. It can be found in the hydrograph that the streamflow in Halsewater decreased after

Table 3
Model Performance Assessed by NSE in Six Tested Catchments

	Name	Original	Adjusted with FEH PR	Adjusted with real PR	FEH UH
1	Tisbury	0.69	−0.11	0.74	−0.84
2	Austins Bridge	0.62	0.55	0.70	0.03
3	Chetnole	0.41	0.47	0.52	0.16
4	Colesbrook	0.20	0.32	0.42	0.29
5	Bishop Hull	0.03	0.25	0.58	0.21
6	Halsewater	0.39	0.71	0.81	0.24

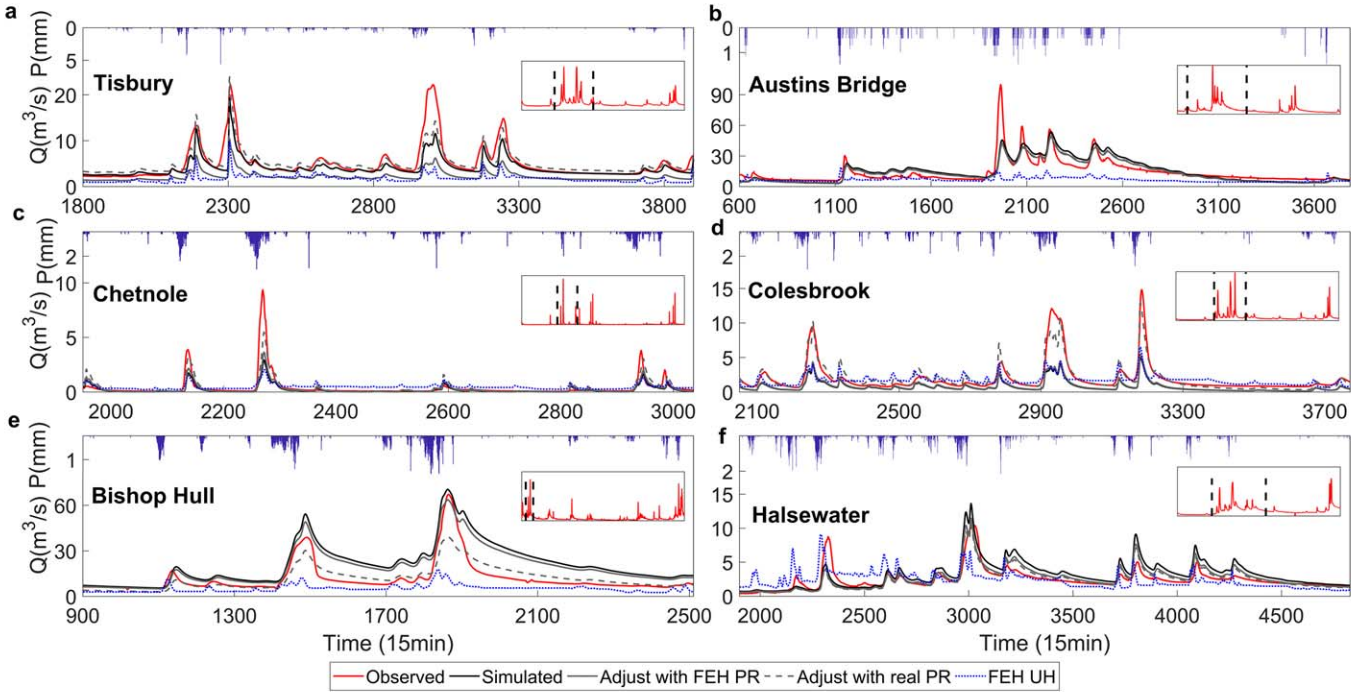

Figure 3. Hydrographs of modeled runoff compared with the observed runoff.

adjusting with the relative error at the largest peak dropped from 32.3% to 11.3%. The adoption of neighbor FEH PR for Tisbury was possible to cause a certain error which brought down the runoff magnitude. For Chetnole, Colesbrook and Bishop Hull, although with higher NSEs, introducing FEH PR did not notably improve the performance based on the hydrographs demonstrated in Figure 3.

3.3. Model Performance Adjusted With Real PR

As PR is investigated to be affected by multiple indexes, including soil, land use, etc. (Merz et al., 2006; Norbiato et al., 2009; Sriwongsitanon & Taesombat, 2011), the FEH PR calculated from the soil map appeared not precise enough. To generate real PR in those catchments, PR was then calculated using the measured and predicted streamflow comparing to the rainfall data in the study period. Another adjustment ratio by comparing the real PR with the predicted PR (predicted PR/real PR) was adopted to further explore the potential improvement of predictions.

The results are shown in Table 3 and hydrographs plotted in Figure 3. It was demonstrated that the model performance was remarkably improved with a large increase of NSE (especially for Halsewater as the adjusted NSE reached 0.81) and better simulated hydrographs. After adjustment, the NSE values in three catchments, i.e., Tisbury, Austins Bridge and Halsewater, were greater than 0.70, which could be treated as acceptable simulations. The NSE values of the other three catchments were still lower than 0.60 even after adjustment with the real PR. Nevertheless, notable improvements can be found in the hydrographs. The relative error at the largest peak in the Colesbrook catchment decreased from 66.8% to 13.6%, and dropped from 75.5% to 45.2% in the Chetnole catchment.

3.4. Model Performance Comparing With FEH UH

The performance was further compared with the FEH UH with NSEs listed in Table 3 and hydrographs illustrated in Figure 3. The catchment geomorphological characteristics were utilized in the FEH UH. Apart from the predictions in the Colesbrook and Bishop Hull catchments, NSEs from the FEH UH were lower than the original model performance with CM. Moreover, it was demonstrated that all NSEs with FEH UH were lower than the CM performance after adjusted with PR. The largest error of peak volume by the FEH UH appeared in Austins Bridge with relative error of 86.6% (the observed flow 98.00 m^3/s, and the predicted flow 13.09 m^3/s). Similar performance can be found in Tisbury, Chetnole, Colesbrook and Bishop Hull. On the contrast, CM performed remarkably better in capturing the flow peaks and hydrograph shapes as the FEH UH underestimated the peaks in all catchments.

4. Discussions

This study presents a novel approach to predict runoff in ungauged catchments with CM [morphing was originally used in image processes changing from one image to another through a seamless transition (Wolberg, 1998)]. CM here is to transport a baseline catchment to a new catchment by changing the catchment characteristics, i.e., area and average slope in this study. Although the created catchment is not exactly the same with the target catchment, significant commonalities exist as catchment area and slope are among the most important indicators that affect runoff generation (Beven & Wood, 1983; D'Odorico & Rigon, 2003; Grimaldi et al., 2010). By predicting the runoff with the created catchment, the generated runoff is assigned with the characteristics of the target catchment. Therefore, it is useful as an alternative for ungauged catchments when it lacks the observed data.

The results demonstrate the feasibility of the approach and a distinct advantage to an empirical unit hydrograph equation described with catchment descriptors. The particular benefit of CM comparing with the geomorphology-based unit hydrograph method is the physical representation of the catchment, averting the over-simplification and the unrealistic assumptions. Moreover, unlike the tremendous demand on the observed data and corresponding uncertainty for commonly used approaches such as regionalization (Westerberg et al., 2016) and empirical equations, it is not necessary for the CM approach application. Only a baseline model and basic catchment geomorphological data of the ungauged catchments are required. Moreover, for the semi-distributed and lumped models adopted in previous studies, the parameters are hard to be derived directly from soil types and land use data although they are correlated to these properties. For the fully distributed model in this study, most of the parameters can be determined from soil types and land use data without recalibration. In addition, common characteristics between the baseline catchment and the target catchment are not essential to create the catchment but crucial in the regionalization approach (Ergen & Kentel, 2016; Swain & Patra, 2017), which broadens its application range in the future.

There is a limitation in this study that the original prediction is not good enough to be directly adopted for another catchment, which is probably because only area and slope are considered. Additional information such as PR is verified helpful to improve the predictions in ungauged catchments based on the results. FEH PR derived from soil types is not absolutely adequate, however, it can still provide some information for how to improve predicted runoff. Especially for ungauged catchments, when the real PR is difficult to obtain, PR from soil types is a useful guidance for runoff prediction.

5. Conclusions

This is the first attempt to predict runoff in ungauged catchments using CM, which is a novel prospect from the traditional methods. With the advantages of less required observed data and simplicity to utilize, CM is promising to a broader application. It should be noticed that the proposed approach is a proof of concept in its early stage to explore the possibility of extrapolating the whole catchment to a new one. Only catchment area and average slope are employed as a simple example of CM in this study. With the development of computer technology, it is possible to produce more complicated morphing catchments, such as landscape fractal (Lifton & Chase, 1992). As a result, more realistic morphing models can be built for ungauged catchments. It should be noted that CM is not a panacea in ungauged catchment modeling. This study should be considered as a starting point to explore CM on runoff prediction (to find out its strengths and weaknesses), and we hope this paper will encourage more studies by the hydrological community to improve the proposed methodology.

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References

Abbott, M. B., Bathurst, J. C., Cunge, J. A., O'Connell, P. E., & Rasmussen, J. (1986). An introduction to the European Hydrological System—Systeme Hydrologique Europeen,''SHE'', 2: Structure of a physically-based, distributed modelling system. *Journal of Hydrology*, *87*(1–2), 61–77.

Bárdossy, A. (2006). Calibration of hydrological model parameters for ungauged catchments. *Hydrology and Earth System Science Discussions*, *3*(3), 1105–1124. https://doi.org/10.5194/hessd-3-1105-2006

Beven, K., & Wood, E. F. (1983). Catchment geomorphology and the dynamics of runoff contributing areas. *Journal of Hydrology*, *65*(1–3), 139–158. https://doi.org/10.1016/0022-1694(83)90214-7

Beven, K. J. (2000). Uniqueness of place and process representations in hydrological modelling. *Hydrology and Earth System Sciences*, *4*(2), 203–213. https://doi.org/10.5194/hess-4-203-2000

Beven, K. J., Wood, E. F., & Sivapalan, M. (1988). On hydrological heterogeneity—Catchment morphology and catchment response. *Journal of Hydrology*, *100*(1–3), 353–375. https://doi.org/10.1016/0022-1694(88)90192-8

Birkinshaw, S. J., & Ewen, J. (2000). Nitrogen transformation component for SHETRAN catchment nitrate transport modelling. *Journal of Hydrology*, *230*(1), 1–17.

Boorman, D. B., Hollis, J. M., & Lilly, A. (1995). *Hydrology of soil types: a hydrologically-based classification of the soils of United Kingdom*. Institute of Hydrology.

Botter, G., Bertuzzo, E., & Rinaldo, A. (2010). Transport in the hydrologic response: Travel time distributions, soil moisture dynamics, and the old water paradox. *Water Resources Research*, *46*, W03514. https://doi.org/10.1029/2009WR008371

Botter, G., & Rinaldo, A. (2003). Scale effect on geomorphologic and kinematic dispersion. *Water Resources Research*, *39*(10), 1286. https://doi.org/10.1029/2003WR002154

Castiglioni, S., Lombardi, L., Toth, E., Castellarin, A., & Montanari, A. (2010). Calibration of rainfall-runoff models in ungauged basins: A regional maximum likelihood approach. *Advances in Water Resources*, *33*(10), 1235–1242.

Chutha, P., & Dooge, J. C. I. (1990). The shape parameters of the geomorphologic unit hydrograph. *Journal of Hydrology*, *117*, 81–97.

Claudia, L., Lebecherel, C., Perrin, V., Andréassian, L. & Oudin, (2016). How should a rainfall-runoff model be parameterized in an almost ungauged catchment? A methodology tested on 609 catchments. *Water Resources Research*, *52*, 4765–4784. https://doi.org/10.1002/2015WR018549

de Hipt, F. O., Diekkrüger, B., Steup, G., Yacouba, Y., Hoffmann, T. & Rode, M. (2017). Applying SHETRAN in a Tropical West African Catchment (Dano, Burkina Faso)—Calibration, Validation, Uncertainty Assessmen. *Water*, *9*(2), 101.

D'Odorico, P., & Rigon, R. (2003). Hillslope and channel contributions to the hydrologic response. *Water Resources Research*, *39*(5), 1113. https://doi.org/10.1029/2002WR001708

Dunn, S. M., McDonnell, J. J., & Vaché, K. B. (2007). Factors influencing the residence time of catchment waters: A virtual experiment approach. *Water Resources Research*, *43*, W06408. https://doi.org/10.1029/2006WR005393

Ergen, K., & Kentel, E. (2016). An integrated map correlation method and multiple-source sites drainage-area ratio method for estimating streamflows at ungauged catchments: A case study of the Western Black Sea Region, Turkey. *Journal of Environmental Management*, *166*, 309–320. https://doi.org/10.1016/j.jenvman.2015.10.036

Ewen, J., Parkin, G., & O'connell, P. E. (2000). SHETRAN: Distributed river basin flow and transport modeling system. *Journal of Hydrologic Engineering*, *5*(JULY), 250–258.

Grimaldi, S., Petroselli, A., Alonso, G., & Nardi, F. (2010). Flow time estimation with spatially variable hillslope velocity in ungauged basins. *Advances in Water Resources*, *33*(10), 1216–1223. https://doi.org/10.1016/j.advwatres.2010.06.003

Grimaldi, S., Petroselli, A., & Nardi, F. (2012). A parsimonious geomorphological unit hydrograph for rainfall–runoff modelling in small ungauged basins. *Hydrological Sciences Journal*, *57*(1), 73–83. https://doi.org/10.1080/02626667.2011.636045

Hrachowitz, M., Savenije, H., Bogaard, T. A., Tetzlaff, D., & Soulsby, C. (2013b). What can flux tracking teach us about water age distribution patterns and their temporal dynamics? *Hydrology and Earth System Sciences*, *17*(2), 533.

Hrachowitz, M., Savenije, H. H. G., Blöschl, G., McDonnell, J. J., Sivapalan, M., Pomeroy, J. W., . . . Cudennec, C. (2013a). A decade of Predictions in Ungauged Basins (PUB)—A review. *Hydrological Sciences Journal*, *58*(6), 1198–1255. https://doi.org/10.1080/02626667.2013.803183

Kelly, S. F., & Cuenca, R. H. (1998). *BOREAS HYD-01 soil hydraulic properties*. Oak Ridge, TN: Oak Ridge National Laboratory Distributed Active Archive Center. Rertrieved form http://www.daac.ornl.gov

Kumar, R., Chatterjee, C., Singh, R. D., Lohani, A. K., & Kumar, S. (2007). Runoff estimation for an ungauged catchment using geomorphological instantaneous unit hydrograph (GIUH) models. *Hydrological Processes*, *21*(14), 1829–1840.

Legates, D. R., & McCabe, G. J. (1999). Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. *Water Resources Research*, *35*(1), 233–241.

Lifton, N. A., & Chase, C. G. (1992). Tectonic, climatic and lithologic influences on landscape fractal dimension and hypsometry: implications for landscape evolution in the San Gabriel Mountains, California. *Geomorphology*, *5*(1–2), 77–114.

Merz, R., Bloschl, G., & Parajka, J. (2006). Spatio-temporal variability of event runoff coefficients. *Journal of Hydrology*, *331*(3–4), 591–604. https://doi.org/10.1016/j.jhydrol.2006.06.008

Naden, P. S. (1992). Spatial variability in flood estimation for large catchments: the exploitation of channel network structure. *Hydrological Sciences Journal*, *37*(1), 53–71. https://doi.org/10.1080/02626669209492561

Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models part I—A discussion of principles. *Journal of Hydrology*, *10*(3), 282–290.

Nippgen, F., McGlynn, B. L., Marshall, L. A., & Emanuel, R. E. (2011). Landscape structure and climate influences on hydrologic response. *Water Resources Research*, *47*, W12528. https://doi.org/10.1029/2011WR011161

Norbiato, D., Borga, M., Merz, R., Blöschl, G., & Carton, A. (2009). Controls on event runoff coefficients in the eastern Italian Alps. *Journal of Hydrology*, *375*(3–4), 312–325. https://doi.org/10.1016/j.jhydrol.2009.06.044

Norouzi Banis, Y., Bathurst, J. C., & Walling, D. E. (2004). Use of caesium-137 data to evaluate SHETRAN simulated long-term erosion patterns in arable lands. *Hydrological Processes*, *18*(10), 1795–1809.

Oudin, L., Andréassian, V., Perrin, C., Michel, C., & Le Moine, N. (2008). Spatial proximity, physical similarity, regression and ungaged catchments: A comparison of regionalization approaches based on 913 French catchments. *Water Resources Research*, *44*, W03413. https://doi.org/10.1029/2007WR006240

Parkin, G. (1996). *A three-dimensional variably-saturated subsurface modelling system for river basins*. Callaghan, NSW: Univeristy of Newcastle.

Rice, J. S., Emanuel, R. E., & Vose, J. M. (2016). The influence of watershed characteristics on spatial patterns of trends in annual scale streamflow variability in the continental U.S. *Journal of Hydrology*, *540*, 850–860. https://doi.org/10.1016/j.jhydrol.2016.07.006

Rigon, R., Bancheri, M., Formetta, G., & deLavenne, A. (2016). The geomorphological unit hydrograph from a historical-critical perspective. *Earth Surface Processes and Landforms*, *41*(1), 27–37. https://doi.org/10.1002/esp.3855

Rinaldo, A., Vogel, G. K., Rigon, R., & Rodriguez-Iturbe, I. (1995). Can one gauge the shape of a basin? *Water Resources Research*, *31*(4), 1119–1127. https://doi.org/10.1029/94WR03290

Robinson, J. S., Sivapalan, M., & Snell, J. D. (1995). On the relative roles of hillslope processes, channel routing, and network geomorphology in the hydrologic response of natural catchments. *Water Resources Research*, *31*(12), 3089–3101. https://doi.org/10.1029/95WR01948

Robson, A., & Reed, D. (1999). *Flood estimation handbook*. Wallingford, UK: Institute of Hydrology.

Rodríguez-Iturbe, I., & Valdes, J. B. (1979). The geomorphologic structure of hydrologic response. *Water Resources Research*, *15*(6), 1409–1420. https://doi.org/10.1029/WR015i006p01409

Savenije, H. H. G. (1996). The runoff coefficient as the key to moisture recycling. *Journal of Hydrology*, *176*(1–4), 219–225. https://doi.org/10.1016/0022-1694(95)02776-9

Sawicz, K. A., Kelleher, C., Wagener, T., Troch, P., Sivapalan, M., & Carrillo, G. (2014). Characterizing hydrologic change through catchment classification *Hydrology and Earth System Sciences*, *18*(1), 273–285. https://doi.org/10.5194/hess-18-273-2014

Singh, P. K., Mishra, S. K., & Jain, M. K. (2014). A review of the synthetic unit hydrograph: From the empirical UH to advanced geomorphological methods. *Hydrological Science Journal*, *59*(2), 239–261. https://doi.org/10.1080/02626667.2013.870664

Sivapalan, M. (2003). Prediction in ungauged basins: A grand challenge for theoretical hydrology. *Hydrological Processes*, *17*(15), 3163–3170. https://doi.org/10.1002/hyp.5155

Soil Parent Material Model. (2011). Tiles: ew280,ew281,ew296,ew297,ew312,ew313 ([SHAPE geospatial data], Scale 1:50000). BGS, Using: EDINA Geology Digimap Service. Retrieved from http://digimap.edina.ac.uk

Sorooshian, S., Gupta, V. K., & Fulton, J. L. (1983). Evaluation of maximum likelihood parameter estimation techniques for conceptual rainfall-runoff models: Influence of calibration data variability and length on model credibility. *Water Resources Research*, *19*(1), 251–259.

Sriwongsitanon, N., & Taesombat, W. (2011). Effects of land cover on runoff coefficient. *Journal of Hydrology*, *410*(3–4), 226–238. https://doi.org/10.1016/j.jhydrol.2011.09.021

Swain, J. B., & Patra, K. C. (2017). Streamflow estimation in ungauged catchments using regionalization techniques. *Journal of Hydrology*, *554*, 420–433. https://doi.org/10.1016/j.jhydrol.2017.08.054

Valdés, J. B., Fiallo, Y., & Rodríguez-Iturbe, I. (1979). A rainfall-runoff analysis of the geomorphologic IUH. *Water Resources Research*, *15*(6), 1421–1434. https://doi.org/10.1029/WR015i006p01421

Westerberg, I. K., Wagener, T., Coxon, G., McMillan, H. K., Castellarin, A., Montanari, A., & Freer, J. (2016). Uncertainty in hydrological signatures for gauged and ungauged catchments. *Water Resources Research*, *52*, 1847–1865. https://doi.org/10.1002/2015WR017635

Wolberg, G. (1998). Image morphing: A survey. *The Visual Computer*, *14*(8), 360–372.

Zhang, J., Han, Song, D. Y., & Dai, Q. (2017). Exploration of virtual catchments approach for runoff predictions of ungauged catchments. *Hydrology and Earth System Science Discussions*, (06), 1–26.

Zhou, G., Wei, X., Chen, X., Zhou, P., Liu, X., Xiao, Y., . . . Su, Y. (2015). Global pattern for the effect of climate and land cover on water yield. *Nature Communications*, *6*, 5918. https://doi.org/10.1038/ncomms6918